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PATENT SPECIFICATION

(11) 1 501 265

(21) Application No. 12247/75 (22) Filed 24 March 1975
(31) Convention Application No. 455583
(32) Filed 28 March 1974 in
(33) United States of America (US)
(44) Complete Specification published 15 Feb. 1978
(51) INT CL² G02B 5/14
(52) Index at acceptance
G2J 34A1 34A5 34B
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(19)

(54) OPTICAL FIBRES

(71) We, WESTERN ELECTRIC COMPANY INCORPORATED, of 222 Broadway, New York, U.S.A., (formerly of 195 Broadway, New York City, New York State, United States of America), a Corporation organized and existing under the laws of the State of New York, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to optical communications systems and, more particularly, to fibre structures suitable for the propagation of optical electromagnetic wave energy.

A variety of fibre waveguiding structures have been proposed in the past few years as transmission media for electromagnetic wave energy in the infrared, visible and ultraviolet portions of the frequency spectrum, collectively designated and considered as the optical region. The most common of these fibre structures consists of a central low optical loss core surrounded by a low optical loss cladding having a lower index of refraction than that of the core. To provide the desired index relationship, the core material is different, or has a different chemical composition, than the cladding material. Because of the non-ideal characteristics of the interface between the cladding and the core, optical disturbances are typically introduced into the modes of optical wave energy transmitted through the core. These disturbances cause various problems, such as the unwanted conversion of guided wave energy from one mode to another with consequent energy loss and distortion. The undesired effects at the core-cladding interface generally limit the minimum losses achievable with such fibres.

Another well-known fibre waveguiding structure is characterized by an index of refraction which is radially graded, that is, which radially decreases in a continuous manner, rather than in a discrete step, from the fibre axis to its outer boundary. The radial refractive index variation is typically parabolic in form. Such a fibre structure eliminates the abrupt interface of the core-cladding fibre, and thus eliminates the undesirable interface effects on the guided wave energy. It, however, requires a continuous (e.g., parabolic) variation in chemical composition from the fibre axis outward to provide the desired radial index variation. Complicated fabrication processes are thus typically required to produce such fibres.

In the article by P. Kaiser, E. A. J. Marcatili, and S. E. Miller in Volume 52 of the *Bell System Technical Journal*, pages 265 to 269 (February 1973), there is disclosed an optical fibre structure which can be formed of a single material having a uniform chemical composition. These fibres include an enlarged central portion connected by one or more thin-film supporting members to a hollow cylindrical outer casing, each of which is preferably formed of the same fibre optical material. Depending upon the relative cross-sectional sizes of the central enlargement, and the thin supporting members in the fibre, optical wave energy can be effectively confined and propagated in and along the central enlargement either in a single mode or in multimodes. The advantages of the single material fibres include freedom from the need for a lower refractive index cladding, and hence freedom from the optical energy losses ordinarily encountered at the core-cladding interface. Moreover, the single material fibre can be readily fabricated from an enlarged preform of such low loss materials as fused silica by heating and drawing the fibre along its longitudinal axis. There are, nevertheless, drawbacks in the single material fibre structures which have been proposed to date. For example, the thin-film supporting members in the fibres must be significantly smaller in cross-section than the central enlargement in order for the latter to be effective in confining the

propagating wave energy. The fibres are thus more delicate than the conventional core-cladding and graded index fibres, and consequently more susceptible to breakage in use. Additionally, the fibres are inherently single channel waveguides, that is, they can accommodate practically only a single central enlargement in and along which an optical wave is propagated. It would be desirable for future optical communication systems to have available a single material optical fibre structure which is comparable in strength to the conventional fibre structures, and which, at the same time, is capable of propagating optical wave energy in a plurality of independent optical channels.

According to the present invention there is provided a fibre for guiding optical electromagnetic wave energy, comprising a unitary optically transparent structure with a centrally disposed elongated filament having a longitudinal axis, and with at least one helicoidal surface ridge surrounding the filament and extending helically along said axis, the cross-sectional dimensions and helical period (p) of the ridge being such that the wave energy can be propagated in at least one guided mode therethrough.

In the preferred embodiment of the present invention, there is provided an optical fibre formed in a unitary integral structure, advantageously of a single material having a uniform chemical composition, and including one or more waveguiding channels in and along which optical wave energy can be propagated. The central portion of the fibre is an elongated filament which has a relatively large cross-sectional size. There is formed on the exterior surface of the central filament at least one helicoidal surface ridge which has cross-sectional dimensions smaller than those of the central filament and which surrounds the filament and extends helically longitudinally therealong. If the cross-sectional dimensions of the surface ridge and the period, or pitch, of its helical path along the filament are properly selected, optical wave energy can be guided in and along the ridge in either single mode or multimode propagation, even though the ridge is formed of the same material as the central filament. There can be provided in the fibre a plurality of such surface ridges which are spaced apart about the exterior surface of the filament. If the spacing between the consecutive ridges is appropriately wide, optical wave energy can be propagated independently in each ridge and the optical channels in the fibre can be effectively separated. With sufficiently large central filaments, optical fibre structures of the embodiment can be constructed to carry as many as 100 separate optical channels.

In a particular illustrative embodiment of the invention, a two-channel single material optical fibre is fabricated with an essentially cylindrical central filament of fused silica. A pair of elongated fused silica rods having cross-sectional dimensions smaller than those of the filament are joined to the exterior surface thereof at diametrically opposite positions and oriented thereon to form two continuous helicoidal surface ridges surrounding the filament and extending helically and longitudinally therealong. A pair of fused silica supporting members are also joined to the exterior surface of the filament at diametrically opposite positions between the helicoidal ridges and are likewise oriented to extend helically along the fibre axis. The supporting members extend radially from the filament through a distance which is greater than that of each ridge and have a thickness which is sufficiently large to provide a mechanical strength for supporting the central filament in the fibre. The height and width of each ridge, and the period, or pitch, of its helical path along the fibre are selected so that an optical signal wave can be effectively confined in each of the two ridges by reason of the waveguiding properties of the structure. The extreme edges of the supporting members are advantageously joined to the interior surface of a hollow fused silica outer cylinder which, in turn, is coated with a layer of an optically absorbing material. The supporting members serve both to provide the desired mechanical support for the central filament in the fibre, and to attenuate higher order modes by carrying their power to the outer absorbing layer.

The helicoidal fibre structure of the embodiment can be fabricated from original fused silica preforms having cross sections which are geometrically similar to, but much larger cross-section than, the final desired structure. The original preform is cleaned, heated and drawn (pulled) in the longitudinal direction in order to reduce the dimensions of the original cross-section to the desired relatively small final cross-section. As the fibre is drawn, and before it is allowed to fully cool, it is twisted, or rotated, about its longitudinal axis at an appropriate rate to provide the desired helicoidal surface configuration.

The invention will be better understood from the following detailed description taken in conjunction with the accompanying drawing in which:

Figure 1A is a longitudinal view of a two-channel optical fibre structure of an embodiment of the invention;

Figure 1B is a cross-sectional view of the optical fibre structure shown in Figure 1A;

Figure 2A is a longitudinal view of a multichannel optical fibre structure of another embodiment of the invention;

Figure 2b is a cross-sectional view of the optical fibre structure shown in Figure 2A;

Figure 3 is a cross-sectional view of an optical fibre embodiment structure including rounded surface ridges;

Figure 4 is a cross-sectional view of a two-channel optical fibre embodiment structure including a protective outer casing; and

Figures 5 to 8 are cross-sectional views of the fibre structures shown in Figures 1B, 2B, 3 and 4, respectively, in an initial stage of fabrication.

Figure 1A shows in longitudinal view, and Figure 1B in cross-sectional view, a simple two-channel helicoidal optical fibre 10. Fibre 10 includes a transparent central filament 11, which illustratively has a cylindrical shape, and a pair of helicoidal surface ridges 12 and 14, which are fused at diametrically opposite positions to the exterior surface of filament 11, and which extend in helical paths along and about the longitudinal axis 15 of filament 11. Advantageously, the filament 11 and the surface ridges 12 and 14 are each made of the same optically transparent material. As will be explained in more detail hereinbelow, the cross-sectional dimensions of each ridge, indicated by a and d in the figures, and the period, or pitch, of its helical path along the filament axis 15, indicated by p in the figures, can be selected so that each ridge is capable of guiding an optical signal wave in a helical wave path along and about axis 15. Thus, fibre structure 10 illustratively has two separate optical channels formed by surface ridges 12 and 14 which guide wave energy even though they are fabricated of the same optical material as that of central filament 11. With the proper choice of the parameters a, d and p for each surface ridge, propagation therein can be either in single mode or in multimodes. Illustratively, one channel (ridge 12) of fibre 10 can be used for transmitting optical signal energy from the end of the fibre shown in the figure to an opposite longitudinal end spaced a large distance (e.g., a kilometer or more) away; the other channel in the fibre 10 (ridge 14) can then illustratively be used for transmitting a return optical signal wave from the distance end of the fibre to the end shown in the figures. Optical source means and optical utilization means (not shown) would thus typically be located at each of the opposite longitudinal ends of fibre 10.

Generally speaking, the radius r of central filament 11 in fibre 10 is selected to be many times the optical wavelength of the wave energy to be propagated through ridges 12 and 14. Preferably, the filament radius r is at least 10 times the optical wavelength, and is typically in the range of about 50 to 1000 times the wavelength. Thus, the embodiment fibre structures are relatively large, and hence, relatively strong and easily handleable.

The cross-sectional width a and the cross-sectional height d of the surface ridges 12 and 14 are selected to be smaller than the filament radius r, but are themselves preferably significantly larger than the optical wavelength to be propagated therethrough. It should be noted generally that the values of the cross-sectional dimensions a and d determine the number of modes capable of propagating in each ridge. It will also be noted from the specific examples set forth and theory discussed hereinbelow that single mode propagation in ridges 12 and 14 can be achieved even though the cross-sectional dimensions of each ridge are ten times greater than the optical wavelength.

If surface ridges 12 and 14 are made of the same optical material as central filament 11, they must have the illustrated helicoidal configuration if they are to be effective in guiding optical wave energy. Single material ridges which extend parallel to filament axis 15, that is, which have an infinite helical period p and a zero angle of pitch α (as seen in Figure 1A) with respect to axis 15, will not be effective guides since wave energy propagating therein will tend to leak therefrom and disperse into the large central filament 11. Effective optical guiding does occur, however, if the single material ridges extend transversely to the filament axis 15 at a suitable angle of pitch α (e.g., greater than about one degree). Theoretically, for optical guidance, the period p of the helical paths of each ridge can be selected to have a value anywhere in the range greater than zero (i.e., an angle of pitch α less than 90 degrees) to about 1000 times the radius r of central filament 11. Relatively small periods may be useful for providing optical delay in the propagating wave energy. For long distance transmission, the period p is preferably in the range of about 1 to 1000 times the filament radius r.

The modes of propagation in the helicoidal fibres of the invention are analogous to the "whispering gallery" modes first observed by Lord Raleigh in sound waves. See Volume V of *Scientific Papers*, page 617, Dover, Cambridge England. As with sound wave, whispering gallery modes in optics tend to cling to the concave boundaries of the medium in

which they propagate. In an optically transmitting fibre, whispering gallery modes are characterized by paths of propagation which are in the form of helices coaxially situated in the fibre and localized slightly below its exterior surface. The essential properties of these modes have been theoretically investigated in terms of ray optics in the article by J. B. Keller and S. E. Rubinow in Volume 9 of *Annals of Physics*, pages 24 to 75 (1960). Those desiring a detailed mathematical model of whispering gallery mode propagation are referred to this article. For the purpose of understanding the principles of the operation of the fibre structures of the embodiment, the following considerations should be adequate.

Consider the fibre structure 10 shown in Figures 1A and 1B in which p denotes the helical period of each guiding ridge and r' the total radius of the fibre

$$(r'=r+d).$$

The local radius of curvature ρ of a given helical wave path in the fibre, measured from the central axis 15, is given by

$$\rho=r'[1+(p/2\pi r')^2]. \qquad (1)$$

If the period p is at least several times larger than the radius r', then

$$\rho=p^2/4\pi^2r'. \qquad (2)$$

Using the mathematical model set forth in the above-cited Keller et al reference, it can be shown that the distance t_m (in the radial direction) below the exterior surface of the fibre within which the wave energy remains localized is given by

$$t_m{}^{3/2}=\frac{3\pi}{4\sqrt{2}}(2m+3/2)k^{-1}\rho^{1/2}, \qquad (3)$$

where ρ is the radius of curvature of the wavepath as given by equation (1) above, m is an integer representing the order (in the radial direction) of the mode propagating in the fibre ($m=0, 1, 2 \ldots$), and k is the propagation constant of the wave in fibre

$$(k=\frac{2\pi}{\lambda}$$

where λ is the optical wavelength in the medium of the fibre). If the fibre has an index of refraction η, then the wavelength λ in the fibre is equal to

$$\frac{\lambda_o}{\eta}$$

where λ_o is the free space optical wavelength.

Effective guidance for the m^{th} order mode (and all lower order modes) in surface ridges 12 and 14 of fibre 10 is provided when the cross-sectional height d of each ridge is selected to be equal in value to t_m for that mode, as determined by Equation (3) above, and when the cross-sectional width a of each ridge is approximately equal in value to d. The dimension a need not be exactly equal to the dimension d; but it is sufficient for optical guidance that a be of the same order of magnitude as d. Preferably, a as in the range of about one to about 3 times d.

Single mode operation in the surface ridges of fibre 10 is provided when only the fundamental ($m=o$) mode is propagated. Assuming $a\approx d$, and substituting $m=0$ into Equation (3) above, the condition for single mode guidance can be written as

$$a^2\approx d^2\approx 0.08\lambda^2(kp)^{2/3}. \qquad (4a)$$

The assumption $a\approx d\approx t_o$ is based essentially on qualitative considerations. A more detailed calculation shows that an accurate expression for the single mode condition is given by

$$ad\approx 0.043\lambda^2(kp)^{2/3}. \qquad (4b)$$

Provided a is not considerably different in value from d, it can be seen that only the cross-sectional area, given by ad, is significant, rather than a and d separately. In the single mode case, modes of higher order than the fundamental extend beyond the ridges both in azimuth and radially; they are thus not confined by the ridges, and are attenuated in the fibre. The field of the fundamental mode, on the other hand, drops off rapidly away from the ridge, and is not attenuated.

As an illustration of the foregoing basic principles, consider the following specific example in which single mode operation is provided in the two-channel single material fibre 10 of Figures 1A and 1B. The material of central filament 11 and surface ridges 12 and 14 is selected to be fused silica (index of refraction $\eta=1.46$), and the wave energy to be propagated through the ridges is selected to have an optical wavelength of about one micrometer. Central filament 11 is provided with radius r of 50 micrometers, and surface ridges 12 and 14 each have a helical period p of about 7 millimeters. It follows from Equation (2) above that the radius of curvature ρ of the helical wavepath in each ridge is approximately 25 millimeters. To provide single mode operation in each of ridges 12 and 14, the cross-sectional dimensions a and d thereof

are selected in accordance with equation (4b) above. Thus, in the illustrative case, single mode propagation is provided in each of the two guiding channels of fibre 10 if

$$a \cong d \cong 8.5 \text{ micrometers.}$$

In order to achieve multimode propagation in surface ridges 12 and 14, the dimensions a and d are typically selected to have values at least several times larger than the calculated values for single mode propagation. For example, in the illustrative case, surface ridges 12 and 14 with dimensions a and d equal to about 50 micrometers would support several modes of a one micrometer optical wave. Reasonably accurate calculations of the ridge dimensions appropriate for multimode propagation can be made using equation (3) above.

The optical fibre structure 10 of Figures 1A and 1B is preferably fabricated in essentially the same manner as the single material optical fibre structures described in the above-cited article by P. Kaiser et al in Volume 52 of the *Bell System Technical Journal*, page 265 (February 1973). It is convenient to start with optically polished fibre segments 51, 52 and 54 in the preform structure 50 shown in cross-sectional view in Figure 5 of the drawing. Typically, all of these segments are made of the same optical material such as fused silica. Preform segment 51 is an essentially straight, cylindrically-shaped rod, and preform segments 52 and 54 are likewise essentially straight rods having smaller, rectangular cross-sections, each of which segment extends directly back along the line of sight into the plane of Figure 5 a suitably large distance. In order to have clean optical surfaces, the exposed surfaces of these segments are first cleaned successively with a suitable cleaning solution, e.g., a solution of trichloroethylene, acetone and nitric acid (1:1 diluted with deionized water) and deionized water. Advantageously, the overall cross-section of the segments in preform structure 50, as initially arranged in Figure 5, constitutes a geometrically similar, but greatly enlarged, cross-section of the finally desired cross-section shown in Figure 1B. After cleaning, preform segments 51, 52 and 54 are heated to a temperature sufficient to fuse them together. While heated, the preform structure is then drawn (pulled) along its longitudinal axis to reduce this cross-section to the finally desired value for optical fibre 10 of Figure 1B. As the fibre is drawn, and before it is allowed to fully cool, it is twisted, or rotated, about its longitudinal axis at an appropriate rate to provide the desired helicoidal surface configuration. If, for example, a helical period p of about 7 millimeters is desired for each guiding ridge, the fibre is steadily rotated through a full 360 degrees about its longitudinal axis for each 7 millimeters of fibre length drawn (i.e., a rotation rate of about 51 degrees per millimeter of drawn fibre). It should be noted that this final twisting step is not employed in the fabrication of the single material fibres of the above-cited P. Kaiser et al article, but is unique to the fibre structures of the present embodiments because of their unique helicoidal configuration. It should also be noted that Figure 5 is not drawn to scale with respect to Figure 1B, but that ordinarily the preform structure 50 is many times larger in cross-section than the final fibre structure 10.

Figure 2A shows in longitudinal view, and Figure 2B in cross-sectional view, a multichannel single material optical fibre 20 embodied in accordance with the invention. Specifically, fibre 20 illustratively includes eight separate ridges, 22.1 to 22.8, which are disposed on the exterior surface of central filament 21 to form eight spaced-apart helicoidal optical channels. As in the simple two-channel fibre 10 of Figures 1A and 1B, each of the surface ridges in fibre 20 can be designed to have a helical period p and cross-sectional dimensions a and d suitable for propagating wave energy in a single mode or in multimodes. Additionally, the propagation in each of the surface ridges can be made independent of the propagation in adjacent ridges (that is, the interaction between the evanescent fields of adjacent channels can be made negligible), if they are spaced apart by sufficiently large distances c along the surface of filament 21. To ensure independent propagation in each channel of fibre 20, the spacing c between adjacent ridges should be at least twice the cross-sectional width a of each ridge (i.e., $c \geq 2a$). This condition is readily satisfied with the fibre structures of the embodiments because of their relatively large cross-sectional size.

If, for example, central filament 21 has a radius r equal to about one millimeter, its circumference ($2\pi r$) is equal to about 6.3 millimeters, or 6300 micrometers. Assuming that the eight ridges 22.1 ... 22.8 are equally spaced about filament 21 and that each ridge has a cross-sectional width a of about 100 micrometers (multi-mode ridges), the spacing between each of the adjacent ridges would be greater than 600 micrometers. It can thus be seen that optical fibre structures like fibre 20 can be fabricated in accordance with the invention to have many independent optical

channels, and are thus analogous to the coaxial cable structures of the conventional lower frequency transmission systems. With a one millimeter radius for central filament 21, for example, 100 separate surface ridges with cross-sectional dimensions *a* and *d* equal to about 20 micrometers, respectively, could be included in the fibre and the spacing *c* between adjacent ridges would still be greater than 2a, or 40 micrometers. Central filaments with even larger radii allow the use of larger numbers of guiding ridges and/or guiding ridges with larger cross-sections.

To fabricate the fibre structure 20 of Figures 2A and 2B, one could illustratively start with the preform structure 60 shown in Figure 6 of the drawing. Preform structure 60 is substantially identical to preform structure 50 of Figure 5, except that the structure 60 includes central segment 61 and eight spaced-apart segments 62.1 to 62.8. Fabrication would illustratively proceed in the same manner as outlined hereinabove with respect to preform structure 50 of Figure 5. Again, it should be noted that the cross-section of preform structure 60 is geometrically similar to, but many times larger than, the cross-section of the desired fibre structure 20 shown in Figure 2B of the drawing.

The cross-section of the guiding ridges in the various embodiments of the invention need not be rectangular, but other contours can also be used which are equally acceptable from an optical point of view. Figure 3 of the drawing shows in cross-sectional view an embodiment of the invention including the rounded guiding ridges. Optical fibre 30 of Figure 3 illustratively includes central filament 31 and two separate surface ridges 32 and 34 which are fused at diametrically opposite positions to the exterior surface of filament 31 and which extend helically into the plane of the figure about the longitudinal axis of filament 31. Ridges 32 and 34 illustratively have an essentially semicircular shape in which the cross-sectional width *a* is approximately equal to twice the cross-sectional height *d*. The desired number of modes to be propagated in ridges 32 and 34 is selected by selecting the cross-sectional height *d* of each ridge to be approximately equal to t_m in accordance with Equation (3) above. Fibre 30 is illustratively identical to fibre 10 of Figures 1A and 1B, with the exception of the cross-sectional shape of ridges 32 and 34.

Figure 7 shows, in cross-section, preform structure 70 which can be used in the fabrication of fibres like fibre 30 of Figure 3. Instead of rectangular ridge segments, preform structure 70 includes two cylindrically shaped ridge segments 72 and 74 which are to be fused to the larger cylindrically shaped segment 71. Fabrication of fibre 30 from preform structure 70 illustratively proceeds as outlined hereinabove.

It is desired for many practical applications that the fibre structure used for the transmission of optical signal waves includes a protective outer jacket which serves, among other purposes, to shield the guiding regions of the fibre structure from disturbances due to handling and other outside influences. A fibre structure embodied in accordance with the present invention to include such a protective outer casing is shown in cross-sectional view in Figure 4 of the drawing. Like fibre 30 of Figure 3, fibre 40 of Figure 4 includes an enlarged central filament 41 and two separate surface ridges 42 and 44 which are fused at diametrically opposite positions to the exterior surface of filament 41 and which extend helically into the plane of the figure about the longitudinal axis of filament 41. Each of ridges 42 and 44 is designed as above to propagate an optical signal wave. A pair of supporting members 43 and 45 is also fused to the exterior surface of filament 41 at diametrically opposite positions between surface ridges 42 and 44 and are likewise oriented to extend helically along the axis of filament 41. Supporting members 43 and 45 extend radially from filament 41 through a distance which is greater than that of each of ridges 42 and 44, and have a thickness which is sufficiently large to provide mechanical strength for supporting filament 41 in the fibre structure. The extreme edges of supporting members 43 and 45 are fused to the interior surface of a hollow outer cylinder 46 which, in turn, is illustratively coated with a layer of an optically absorbing material 48. Advantageously, each of filament 41, ridges 42 and 44, supporting members 43 and 45 and outer cylinder 46 in fibre 40 is formed of the same optical material, such as fused silica.

The thickness of supporting members 43 and 45 indicated by *b* in Figure 4, is fabricated typically to be substantially larger than the propagating optical wavelength in order to provide the desired mechanical support for filament 41. It will be noted that, unlike the thin-film supporting members involved in the single material fibres of the above-cited P. Kaiser et al reference, supporting members 43 and 45 need not be of smaller cross-section than the guiding regions in fibre 40 (i.e., than ridges 42 and 44). In addition, supporting members 43 and 45 extend radially from the exterior surface of filament 41 through a distance which is at least ten times larger than the wavelength to provide sufficient

space in the cavity defined by filament 41 and the interior surface of outer cylinder 46. Such a cavity would typically be occupied by air ($\eta \approx 1.00$). As an example, if the cross-sectional height d of ridges 42 and 44 is about 20 micrometers and the optical wavelength to be propagated there is about one micrometer, supporting members 43 and 45 would illustratively have a thickness b of at least about 30 micrometers and would extend radially from filament 41 by at least about 60 micrometers. Of course, if larger cross-sectional ridges are employed, supporting members 43 and 45 would have correspondingly larger cross-sectional dimensions.

In addition to providing mechanical support for central filament 41 of fibre 40, supporting members 43 and 45 serve another useful purpose in the guiding structure. As noted previously modes of orders higher than that for which ridges 42 and 44 are designed to propagate tend to extend in azimuth and radially above and beyond the ridges in the fibre, and thus are not confined thereby. The supporting members 43 and 45 serve a useful purpose of carrying the power of these undesired higher order modes to outer cylinder 46 where they can be quickly absorbed by the optically absorbing layer 48 without affecting significantly the propagation of the selected modes.

Figure 8 shows in cross-sectional view a preform structure 80 suitable for fabricating fibre structures like fibre 40 of Figure 4. The segments of preform structure 80 which corresponds to the elements of fibre 40 shown in Figure 4 are numbered 40 units higher in Figure 8. After fibre 40 is fabricated from preform 80 as outlined hereinabove, the fibre is illustratively coated by known techniques with a layer of optically absorbing material such as methyl methacrylate.

Although the invention has been described in terms of specific embodiments, it should be understood that various alternative modifications can be made. For example, although all of the specific embodiments illustrated in the drawing include two or more helicoidal surface ridges, it is possible to include in the fibre only a single helicoidal surface ridge in and along which optical wave energy is to be propagated. Such a single channel fibre may be particularly useful as an optical delay line for a guided optical wave. Various optically transparent materials in addition to fused silica can be used for the various elements of the fibre structures illustrated. Although these elements are preferably all the same optical material, they need not be so, as long as they can be fused together as described. The particular technique described for fabricating the fibres is not exclusive, but other alternative fabrication techniques may be realized by those skilled in the art. Moreover, the parameters specified for the various elements of the above fibre structures are illustrative only, and not intended to be of a limiting nature. The optimum choice of parameters for any particular application of the invention is best determined experimentally by the skilled worker in light of the foregoing specific examples.

Furthermore, although not preferred, the entire exposed surface of fibres 10, 20 and 30 above could be coated with a layer of a lower refractive index cladding material to provide suitable protection for the fibre. Also, to furnish optical interaction with the modes propagating through the fibres of the embodiments, a suitable optically nonlinear material can be placed in contact with the guiding regions along selected lengths of the fibre. For example, in fibre 40 of Figure 4, a selected portion of the cavity between filament 41 and outer cylinder 46 could be filled with an optically nonlinear material selected from such well known materials as Rhodamine 6G in water or methanol, ethyl alcohol, chlorobenzene, or carbon disulfide. Optical gain, optical frequency mixing, and other optical interactions would thus be conveniently provided in the fibres.

Finally, an optical cable, containing many similar fibres of this invention, could be fabricated by incorporating these fibres in a single peripheral structure of suitable size and cross-section. The cable would typically include suitable means for holding the various fibres rigidly in place and for maintaining an adequate separation therebetween.

WHAT WE CLAIM IS:—

1. A fibre for guiding optical electromagnetic wave energy, comprising a unitary optically transparent structure with a centrally disposed elongated filament having a longitudinal axis, and with at least one helicoidal surface ridge surrounding the filament and extending helically along said axis, the cross-sectional dimensions and helical period (p) of the ridge being such that the wave energy can be propagated in at least one guided mode therethrough.

2. A fibre according to Claim 1, wherein the filament and the helicoidal surface ridge are formed of the same transparent material.

3. A fibre according to Claim 1 or 2, wherein the filament has a substantially circular cross-section of radius (r) at least ten times greater than the wavelength of the

wave energy to be propagated through the ridge.

4. A fibre according to Claim 3, wherein the helical period (p) of the ridge is in the range of one to 1000 times the radius (r) of the filament.

5. A fibre according to Claim 4, wherein the ridge has a substantially rectangular cross-section with a cross-sectional height (d) above the exterior surface of the filament which is greater in value than the wavelength of the wave energy to be propagated therethrough, and a cross-sectional width (a) which is in the range of one to three times the cross-sectional height (d).

6. A fibre according to Claim 4, wherein the ridge has a rounded cross-section with a cross-sectional height (d) above the exterior surface of the filament which is greater in value than the wavelength of the wave energy to be propagated therethrough and a cross-sectional width (a) which is in the range of one to three times the cross-sectional height (d).

7. A fibre according to Claim 5, wherein the cross-sectional width (a) of the ridge is substantially equal in value to the cross-sectional height (d), and wherein the width a and height d are selected such that the relationship

$$ad=0.043\lambda^2(kp)^{2.8}$$

is substantially satisfied, where λ is the optical wavelength of the wave energy to be propagated in the ridge, k is equal to $2\pi/\lambda$, and ρ is given by

$$\rho=r[1+(p/2\pi r)^2],$$

where r is the radius of the central filament and p is the helical period of the ridge, whereby only a single mode of the wave energy is propagated in the ridge.

8. A fibre according to Claim 1, including a plurality of helicoidal surface ridges spaced apart about the exterior surface of said filament, the spacing c between adjacent surface ridges being at least twice the cross-sectional width a of each of the ridges.

9. A fibre according to any one preceding claim, comprising at least two helical supporting members fused to the exterior surface of said filament at respective positions spaced from the helicoidal surface ridge or ridges, said supporting members extending radially from the exterior surface of the filament a distance greater than the or each ridge, the extreme edges of the supporting members being fused to the interior surface of a hollow outer casing of a material which is transparent to the wave energy to be propagated in the ridge(s), whereby a cavity is defined in the fibre between the exterior surface of the central filament and the interior surface of the hollow outer casing.

10. A fibre according to Claim 9, wherein the filament, the helicoidal surface ridge(s), the supporting members, and the hollow outer casing are each formed of the same transparent material.

11. A fibre according to Claim 9, wherein the supporting members have a thickness b which is at least an order of magnitude greater than the wavelength of the optical wave energy to be propagated in the ridge(s).

12. A fibre according to Claim 9, 10 or 11, wherein the exterior surface of the hollow outer casing is coated with a layer of an optically absorbing material.

13. A fibre according to Claim 9, 10, 11 or 12, wherein at least a portion of the cavity defined by the exterior surface of the filament and the interior surface of the hollow outer casing is occupied by an optically nonlinear material for interaction with the optical radiation to be propagated in said ridges.

14. A fibre according to Claim 2 or any claim appendant thereto, wherein the transparent material is fused silica.

15. A fibre for guiding electromagnetic radiation, substantially as hereinbefore described with reference to Figures 1A, 1B and 5, or Figures 2A, 2B and 6, or Figures 3 and 7, or Figures 4 or 8, of the accompanying drawings.

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Printed for Her Majesty's Stationery Office, by the Courier Press, Leamington Spa, 1978
Published by The Patent Office, 25 Southampton Buildings, London, WC2A 1AY, from which copies may be obtained.

1501265 COMPLETE SPECIFICATION

2 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 1

FIG. 1A

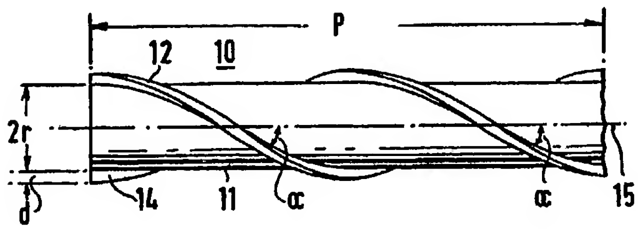

FIG.1B

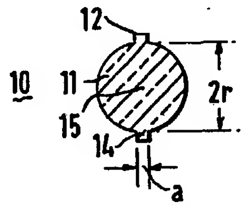

FIG 3

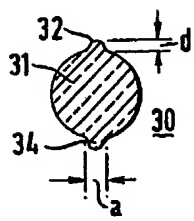

FIG.4

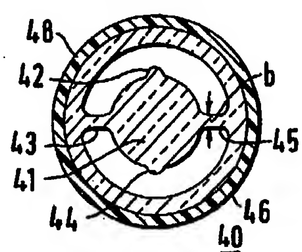

FIG. 2A

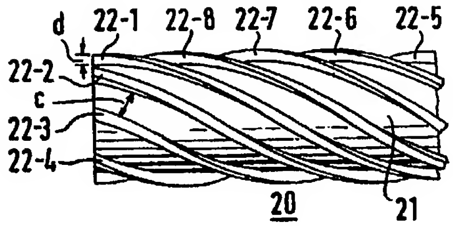

FIG. 6

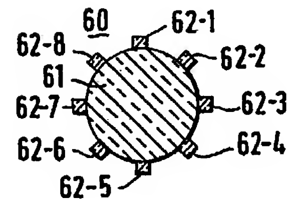

FIG. 2B

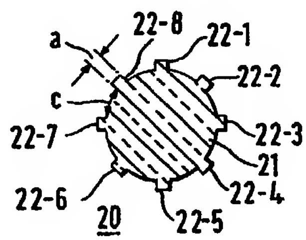

FIG. 7

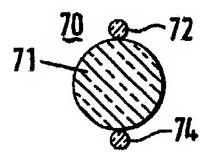

FIG. 5

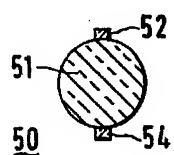

FIG. 8